Micrometeorites from the Transantarctic Mountains

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We report the discovery of large accumulations of micrometeorites on the Myr-old, glacially eroded granitic summits of several isolated nunataks in the Victoria Land Transantarctic Mountains. The number (>3,500) of large (>400 μm and up to 2 mm in size) melted and unmelted particles is orders of magnitudes greater than other Antarctic collections. Flux estimates, bedrock exposure ages and the presence of ≈0.8-Myr-old microtektites suggest that extraterrestrial dust collection occurred over the last 1 Myr, taking up to 500 kyr to accumulate based on 2 investigated find sites. The size distribution and frequency by type of cosmic spherules in the >200-μm size fraction collected at Frontier Mountain (investigated in detail in this report) are similar to those of the most representative known micrometeorite populations (e.g., South Pole Water Well). This and the identification of unusual types in terms of composition (i.e., chondritic micrometeorites and spherulitic aggregates similar to the ≈480-kyr-old ones recently found in Antarctic ice cores) and size suggest that the Transantarctic Mountain micrometeorites constitute a unique and essentially unbiased collection that greatly extends the micrometeorite inventory and provides material for studies on micrometeorite fluxes over the recent (≈1 Myr) geological past.

Antartica | cosmic spherules | solar system composition | unmelted micrometeorites | scoriaceous micrometeorites

Micrometeorites (particles normally less than ≈1 mm in size) constitute the main part of the flux of extraterrestrial matter accreting on Earth (1–3). Quantitative estimates of this flux in terms of amount and composition are thus important for understanding the cycles of extraterrestrial input to the global geochemical budget of planet Earth. Moreover, because micrometeorites may sample a different kind of extraterrestrial matter than meteorites (2), they are very important to understanding the composition of the solar system. A number of micrometeorite collections have been studied previously, including those from deep-sea sediments (1, 4, 5), from secondary concentrations due to the natural melting of glacier ice in Greenland (6), Antarctica (7, 8) and Novaya Zemlya (9), and from artificially melted glacier ice and snow in Antarctica (3, 10–12). Micrometeorites have also been recovered from a variety of terrestrial surfaces (desert soils, beach sands, etc.) (13), showing that their ubiquitous deposition can be evidenced on any surface, provided that the accumulation time is sufficient, weathering is low, and discrimination from terrestrial particles is feasible. One major pending question that justifies the comparative study of the various collections is how the collection setting biases the characteristics of extraterrestrial matter, in terms of type, grain size, hardness, and resistance to weathering. Moreover, the age and duration of the sampled flux is often quite short (in the 100- to 1,000-yr range) or unknown, hindering the detection of possible flux variability over time.

During the Italian 2003 and 2006 *Programma Nazionale delle Ricerche in Antartide* (PNRA) expeditions, we discovered a micrometeorite trap on the tops of the Transantarctic Mountains in Victoria Land (Fig. 1) that may provide insight into these 2 issues. Thousands of micrometeorites up to 2 mm in size were found within the fine-grained bedrock detritus accumulated in the joints and decimeter-sized weathering pits of flat, glacially eroded granitoid summits. These structures trap micrometeorites over the Myr time scale, as testified by the ≈0.8-Myr-old Australasian microtektites found therein (14).

Through size-distribution and frequency-by-type studies of micrometeorite samples collected at Frontier Mountain and the identification of unusual types, we provide evidence that the Transantarctic Mountain micrometeorite collection is a unique and essentially unbiased collection representing a long record of micrometeorite flux over the recent geological past.

Geological Setting

Frontier Mountain (Fig. 1*A*) has been a very productive site for meteorite collection in the 7 EUROMET and PNRA expeditions (15). In the 2001 expedition, a meteorite (FRO 01149) was incidentally found, on the top of the mountain during a geomorphological survey. The meteorite was found at an altitude of ≈2,775 m (i.e., ≈600 m above the present-day ice level), sitting on a glacially eroded surface generated by an ice sheet that overrode Frontier Mountain during a past glaciation (Fig. 1*B*). The ^{26}Al, ^{10}Be, and ^{21}Ne cosmogenic nuclide concentrations of 2 surface granite samples yielded an exposure age of 4.4 Myr. FRO 01149, with a terrestrial age of ≈3 Myr, is the oldest stony meteorite discovered on Earth (fossil meteorites excluded) (16). These findings suggest that the only source of allochthonous material deposited onto this surface since the last local retreat of the Antarctic ice sheet >4 Myr ago is atmospheric fallout including tephra, micrometeorites, and microtektites.

The unusual finding of the FRO 01149 meteorite prompted a second more-thorough search for meteorites at the top of the mountain during the 2003–2004 PNRA expedition. Searches were conducted with the help of a magnetic gradiometer that proved an efficient tool to locate 3- to 20-g meteorites buried in snow during the same expedition (17). Although no meteorites were found on that occasion, the magnetic gradiometer led us to the discovery a large accumulation of micrometeorites. A granitic glacial surface contained scattered weathering pits 10–30 cm in diameter and 5–15 cm in depth. Most of these depressions were empty, but the largest (extending for ≈0.07 m^2), was two-thirds filled with granitic detritus and produced a local magnetic maximum (Fig. 1*C*). Below the wind-sorted gravel and sand, there was a darker and finer material with higher magnetic susceptibility than the granite, thus explaining the magnetic signal in the absence of any meteorite. At the base of the depression, the material was coherent, and looked like loess,

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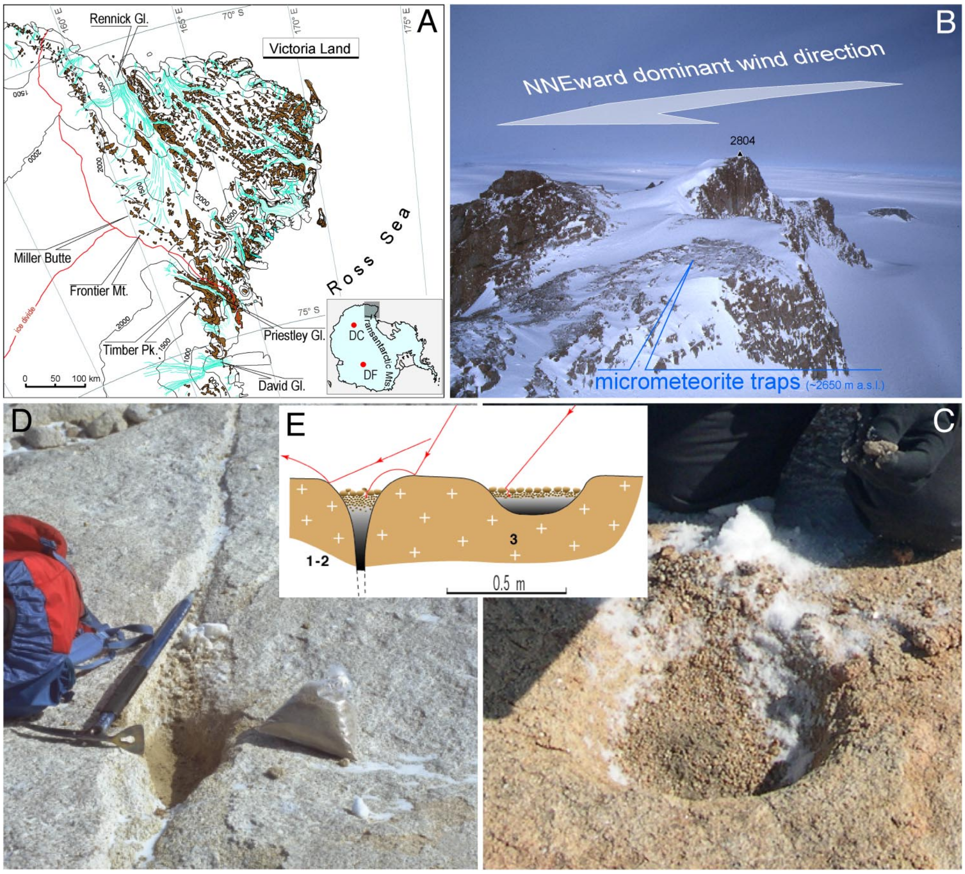

Fig. 1. Transantarctic Mountain micrometeorite traps. (*A*) Sketch map of Victoria Land showing locations at Frontier Mountain, Miller Butte, and Timber Peak where micrometeorites were found. Brown areas represent exposed bedrock, whereas blue and red lines indicate ice flows and ice divides, respectively. (*Inset*) Sketch map of Antarctica showing the location of Victoria Land (shaded area) and EPICA Dome C (DC) and Dome Fuji (DF) ice cores (red dots). (*B*) Aerial view of the top of Frontier Mountain (72°58′ S, 160°30′ E, 2,804 m). (*C*) A type of micrometeorite trap in a weathering pit of a flat granitic surface (sample 3). (*D*) A second type of micrometeorite trap in a granite joint (sample 1). (*E*) Sketch of the proposed accumulation mechanism in the 2 types of micrometeorite traps.

with low density and visible bubble-like cavities. Sample 3 was collected by hand from this lower layer. The other positive magnetic detections (samples 1 and 2, Fig. 1*D*) occurred in a different setting, namely along eroded granitic joints. A total of 1 kg of <2-mm detritus was recovered in 2003 [supporting information (SI) Tables. S1 and S2]. As later revealed by laboratory investigations, the magnetic signals were mainly generated by tephra and thousands of micrometeorites (Tables S1 and S2). In 2006, we thus collected an additional 177 kg of detritus mainly from Frontier Mountain, Miller Butte, and an unnamed nunatak in the Timber Peak area (samples 4–27; Tables S1 and S2).

Fig. 1*E* illustrates the hypothesized mechanism for the accumulation of atmospheric fallout in the 2 types of trap, once a sufficient depression has been generated by weathering and granite disaggregation. During strong winds, no deposition occurs, and size sorting limits the deflation of finer particles, allowing their percolation to the bottom of the depression through an equilibrium layer of coarser granitic detritus. During periods of calm, vertically falling particles will likely be caught inside the gravel layer, ensuring an efficient capture. A snow cover may also lead to no accumulation: Although snow can efficiently trap the falling particles, they will inevitably be wind blown upon snow sublimation unless they are able to make their way to the gravel level.

Sample Preparation and Measurement Techniques

Soil samples 1, 2, and 3 were dried by using vacuum pumping and subsequently dry-sieved through the following meshes: 800, 400, 200, and 100 μm. In this report, we focus on the 4 fractions >100 μm because the extraordinary number and size of large micrometeorites in our collection represent a novelty in micrometeorite research (the smaller fractions remain to be investigated in future works). Micrometeorites were magnetically and visually extracted under the stereo microscope (Tables S1 and S2). Extraterrestrial spherules were easy to identify under the stereo microscope in all magnetic fractions whereas abundant dark, angular, terrestrial grains (mostly tephra) in the <400-μm fraction made the identification of unmelted micrometeorites more difficult. Whole-specimen observations were conducted in a microanalytical scanning electron microscope (SEM-EDS) on particles >200 μm from samples 2 and 3. Lastly, all particles >400 μm and most spherules from the 200- to 400-μm fractions of samples 2 and 3 were embedded in epoxy and sectioned for petrographic investigations under the SEM and bulk chemical analyses by means of electron microprobe (Tables S3 and S4). Extraction from samples 4–27 (the 2006 collection) remains to be completed by following similar procedures, and only preliminary data will be presented in this work.

Micrometeorite Concentration, Size Distribution, and Collection Duration

The number of unmelted micrometeorites identified in the >200-size fractions of samples 2 and 3 are 25; counting for samples 1, 2, and 3 yielded 22 and 3,282 spherules in the >400 and 100- to 400-μm fractions, respectively (Tables S1 and S2). The number of spherules is nearly equal to that obtained by

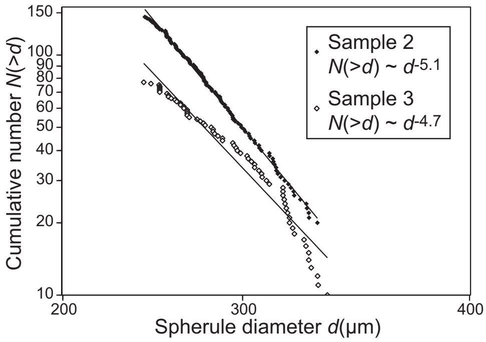

Fig. 2. Cumulative size distribution for Frontier Mountain micrometeorites (cosmic spherules only) in the >200-μm size range for samples 2 (filled diamonds; n = 158) and 3 (open diamonds; n = 65) collected in the joint and weathering pit, respectively, featured in Fig. 1. Distribution is cut at a spherule diameter of 240 μm to account for bias introduced by sieving, and at $n \leq 10$ for statistical representativeness (see Fig. S1 to view the full distribution).

melting 100 tons of Antarctic blue ice (10), i.e., a concentration of extraterrestrial material 10^5 times higher than in blue ice.

The size of the spherules, measured on whole specimens in the SEM, was used to produce the cumulative size distribution in Fig. 2 (see also Fig. S1). The linear fit in log–log scale for samples 2 and 3 >240 μm yields an exponent of -5.1 ± 0.2 and -4.7 ± 0.4, respectively. Although a minor deficit is observed in the smaller size fraction, these values compare well with the exponents of -5.2 and -5.4 obtained for the South Pole Water Well cosmic spherule collection (18, 19), which is considered to best represent the modern (≈1500–800 AD) flux of micrometeorites. This match excludes significant size sorting in the >200-μm size fraction because of the accumulation mechanism and suggests that our collection is not a secondary concentration by wind transport like the one found at Walcott Névé (8). This conclusion is based on the -2.8 ± 0.3 exponent that we obtained for a Walcott Névé sample of 140 spherules (Fig. S1), which indicates preferential loss of small, wind-blown particles.

During our preliminary work on the >400-μm fraction of the 2006 collection (samples 4–27; Tables S1 and S2), we separated 3,398 cosmic spherules and 135 unmelted micrometeorites up to 2 mm in size (Fig. 3). This population is much greater than that of large micrometeorites in collections worldwide: For instance, "only" 136 particles in the 400- to 1,000-μm size range have been hitherto reported from the richest collection so far, i.e., the South Pole Water Well collection (19).

To estimate the time span during which micrometeorite collection occurred, our analysis is restricted to circular pits, for which the capture surface can be assumed to be the depression surface. From the study of the South Pole Water Well micrometeorite collection (18), we calculate a flux rate of spherules >100 μm of 0.17 yr^{-1} m^{-2} (total number counted: 1,131). Using the surface area of the site 3 pit (0.07 m^2) and the counted spherules (1,497), we derive a deposition time of 130 kyr. The same calculation for another pit from Miller Butte (18c) similar to that of sample 3 yields a 500-kyr duration. ^{10}Be-derived exposure ages (see ref. 20) for experimental procedure) of the quartz grains of the local detritus within the traps are 0.32 ± 0.15 and 0.98 ± 0.10 Myr for samples 1 and 3, respectively (Table S5), i.e., in the same range as the estimated accumulation duration, the FRO 01149 meteorite terrestrial age and the bedrock exposure age.

Number and Types of Micrometeorites and Remarkable Findings

The mineral and bulk chemical composition of 264 sectioned particles studied by electron microscopy further documents their extraterrestrial origin (Tables S3 and S4). The studied set

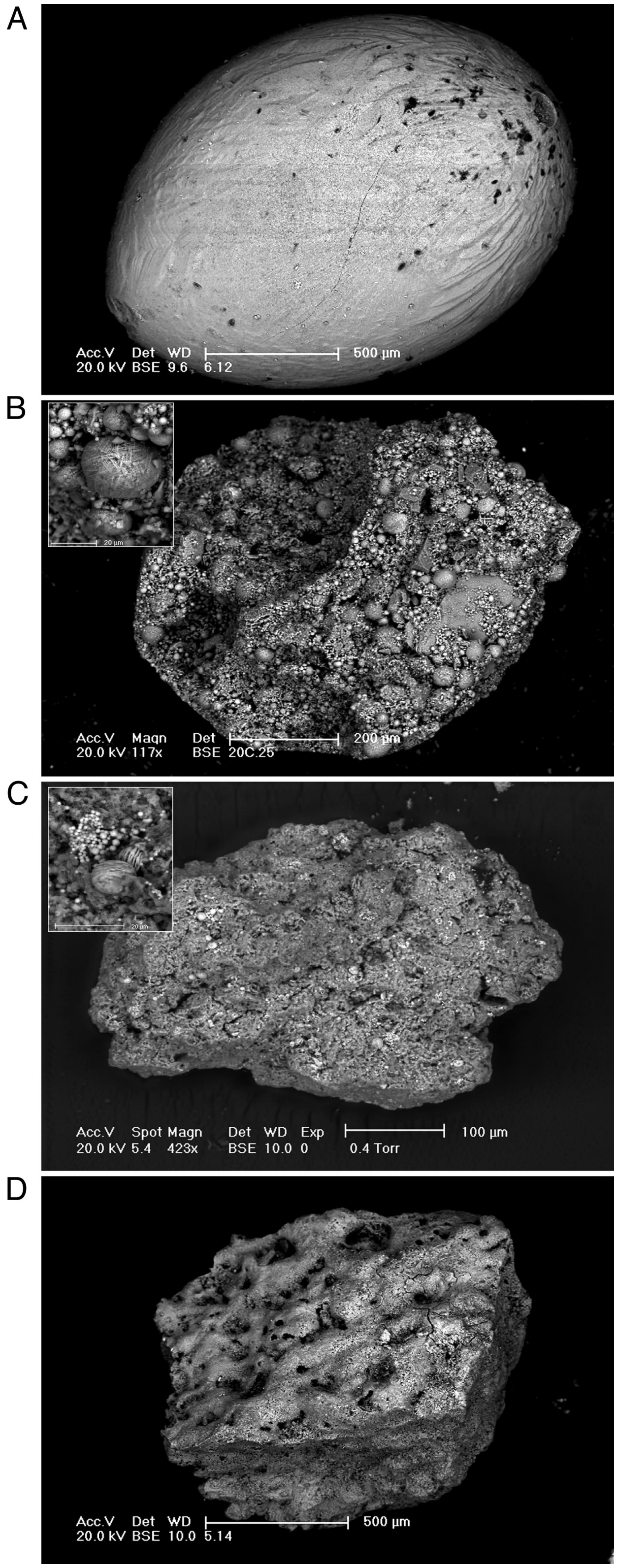

Fig. 3. Transantarctic Mountain micrometeorites (back-scattered electron images): a selection of large specimens. (*A*) A microcrystalline cosmic spherule (6.12) with a maximum elongation of ≈2 mm. (*B*) An ungrouped spherulitic aggregate (20c.25). (*Inset*) Detailed view of the constituting spherules mainly consisting of Fe-oxide dendrites. (*C*) An unmelted fine-grained, C-type micrometeorite (2.1c) ≈400 μm across. (*Inset*) Magnetite framboids. (*D*) An unmelted micrometeorite ≈1 mm in size showing a scoriaceous fusion crust (5.14).

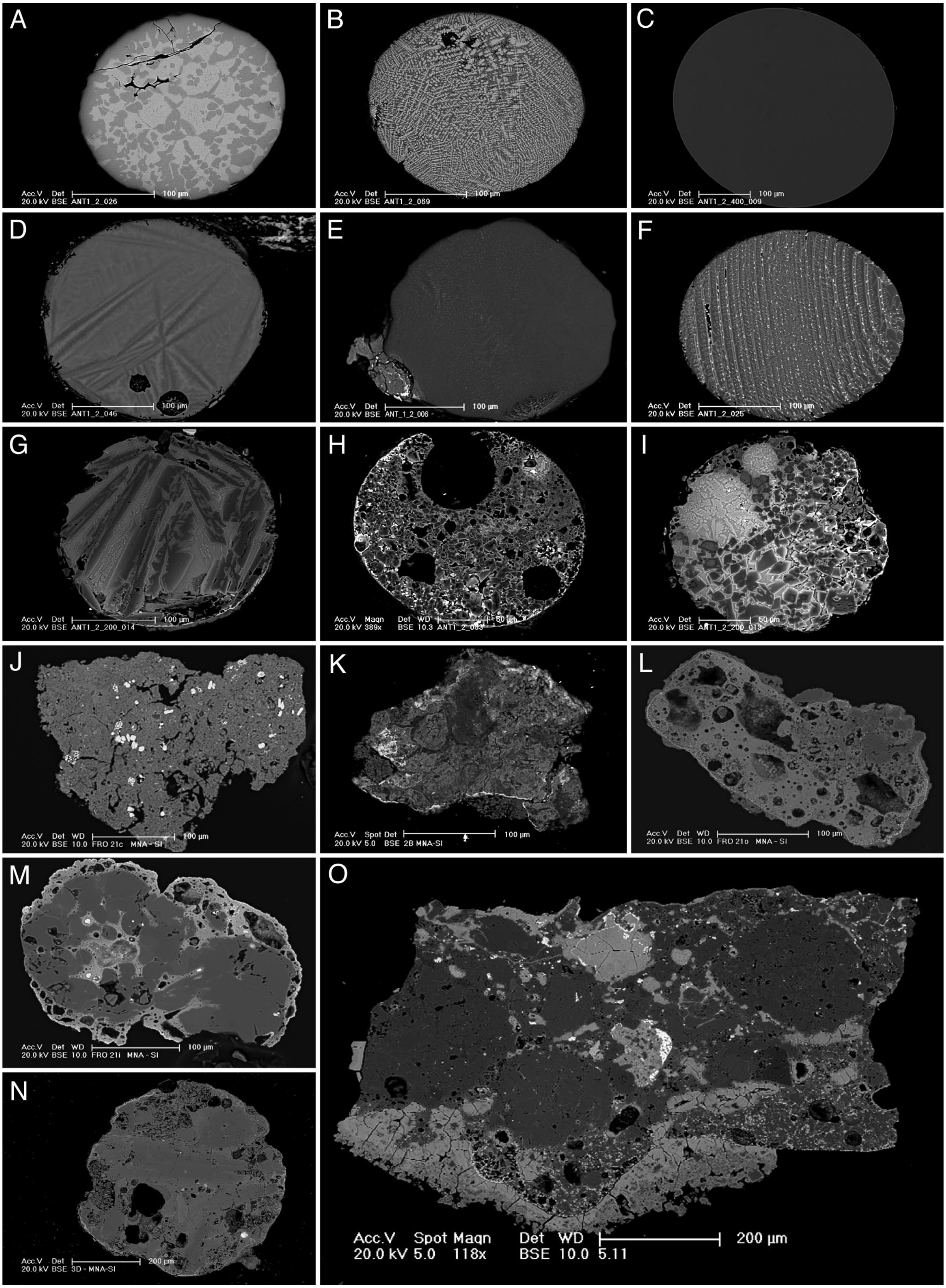

Fig. 4. An inventory of micrometeorite types in the Transantarctic Mountain collection (back-scattered electron images of sectioned and polished micrometeorites). (*A*) An I-type cosmic spherule dominated by magnetite and wüstite intergrowths. (*B*) A G-type cosmic spherule dominated by dendritic magnetite. (*C*) A V-type (vitreous) cosmic spherule (namely a CAT subtype) (2.9). (*D*) An S-type (stony) vesicular cryptocrystalline cosmic spherule (2.46). (*E*) An S-type microcrystalline cosmic spherule (2.6). (*F*) An S-type barred olivine cosmic spherule (2.25). (*G*) An S-type porphyritic cosmic spherule with relatively coarse-grained olivine microphenocrysts (2.14). (*H*) An S-type vesicular porphyritic cosmic spherule with relatively fine-grained olivine microphenocrysts (2.33). (*I*) An S-type, relict bearing, porphyritic olivine cosmic spherule (2.13). (*J*) A C1-type unmelted micrometeorite (see also Fig. 2*C*) (2.1c) (*K*) A C2-type fine-grained unmelted micrometeorite (2B). (*L*) A partially melted scoriaceous micrometeorite (2.1o). (*M*) An unmelted coarse-grained micrometeorite (2.1i) consisting of 2 porphyritic chondrules (see also Fig. S2). (*N*) An unmelted coarse-grained micrometeorite (3D) consisting of a single porphyritic chondrule. (*O*) An unmelted coarse-grained micrometeorite (5.11) with a chondritic structure (see also Fig. 2*D* and Fig. S2). Note that micrometeorites featured in *G*–*I* and *K*–*O* are partly or entirely mantled by magnetite rims.

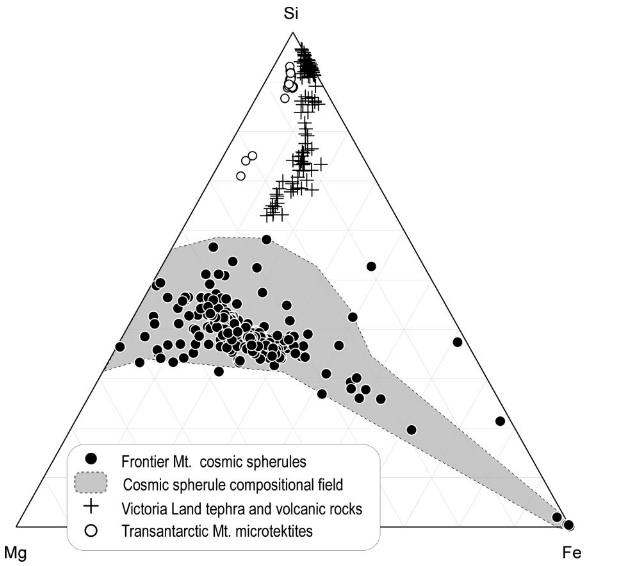

Fig. 5. Mg-Si-Fe (atoms) ternary diagram showing where Transantarctic Mountain micrometeorites (cosmic spherule from Frontier Mountain only) plot relative to other Antarctic, Greenland, and deep-sea cosmic spherules (18), Victoria Land tephra embedded in ice (24), and volcanic rocks (25), and Transantarctic Mountain microtektites (14).

includes cosmic spherules, and unmelted and scoriaceous micrometeorites.

A set of 233 spherules from the 200- to 400-μm size fractions of samples 2 and 3 includes 3% iron type (I-type) spherules consisting mainly of magnetite–wustite intergrowths (Fig. 4*A*), 1% G-type spherules consisting mainly of magnetite dendrites in a silicate glass mesostasis (Fig. 4*B*), 20% V-type spherules consisting of glass (Fig. 4*C*), and 76% S-type spherules consisting of glass, olivine (Fa_{1-47}), and magnetite assemblages with cryptocrystalline (including one Ca-Al-Ti-rich, CAT, spherule; Mg/Si = 1.73), barred and porphyritic olivine textures (Fig. 4 *D–I*). The statistics by type is therefore similar to the South Pole Water Well and Greenland collections (18), which are considered the least-biased collections so far known. The lack of enrichment in denser types (i.e., I- and G-types) and of depletion in lighter and more fragile types (V-types, including hollow spherules) is a further strong indication of minor wind sorting and weathering bias. The bulk composition of Frontier Mountain spherules is similar to that from other Antarctic and non-Antarctic collections and obviously distinct from both the volcanic fallout in the Frontier Mountain region and Transantarctic Mountain microtektites (Fig. 5).

Of the 13 and 12 angular-to-subrounded particles from the 200- to 800-μm fraction of samples 2 and 3, respectively, 7 consists of compact fine-grained mineral assemblages similar to the matrix of C1 (Fig. 4*J*) and C2 (Fig. 4*K*) carbonaceous chondrites, 12 are scoriaceous micrometeorites consisting of highly vesicular melt hosting sparse relic grains mainly of forsteritic olivine and enstatitic pyroxene up to $\approx$100 μm in size (Fig. 4*L*), and 6 are coarse-grained micrometeorites consisting mainly of forsterite and/or enstatite igneous crystals up to $\approx$300 μm in size. Remarkably, 1 of the latter contains 2 type-I porphyritic chondrules (Fig. 4*M* and Fig. S2) and another one (Fig. 4*N*) is a type-II chondrule consisting mainly of olivine ($Fa_{25.6}$), enstatite ($Fs_{20.8}$ $Wo_{2.0}$), chromite, and Fe-Ni metal (Ni = 5.4 wt%). Although possible chondrule-like objects have been described by other researchers in relatively small (< 200 μm) micrometeorites (e.g., ref. 21 and recent abstracts by S. Taylor and M. J. Genge), the relatively large size of Transantarctic Mountain micrometeorites allowed the unequivocal identification of chondritic structures for the first time (Fig. 4 *M* and *O*). This finding conclusively ties part of the micrometerite flux to chondritic material, likely carbonaceous and/or (in agreement with ref. 22) ordinary chondrites.

Six subrounded-to-subangular particles in the 800- to 2,000-μm size range from an additional sample from Frontier Mountain (sample 5) have ordinary chondritic structure and mineralogy. Four particles show readily-to-poorly delineated chondrules (Fig. 4*O*) typical of low- and intermediate-metamorphic grades (petrographic types 4 and 5), whereas 2 others exhibit coarse-grained granoblastic textures typical of high-grade metamorphism (petrographic type 6). The average olivine and low-Ca pyroxene compositions in the various particles varies from Fa_{18} Fs_{17} to Fa_{26} Fs_{22}, respectively, indicating H and L ordinary chondritic chemical classes. Other minerals include high-Ca pyroxene, chromite, Fe-sulfide, Ni-rich iron oxides (as likely weathering products on metal grains), and oligoclase (in granoblastic particles only). One H- and one L-chondritic particle are mantled by a quench-textured igneous layer similar to the fusion crust observed in stony meteorites; this layer is then mantled by a magnetite shell typically observed in unmelted or scoriaceous micrometeorites (Fig. 4*O* and Fig. S2). This is another outstanding finding that relates some of the extraterrestrial flux of micrometeorites to ordinary chondritic material also in the large 800- to 2,000-μm size fraction. The other 4 particles did not show a continuous magnetite shells and may possibly be fragments of even larger particles or meteorite ablation debris.

Remarkably, 2 identical, highly unusual particles (Fig. 3*B*) $\approx$700 μm in size were found on the top of Miller Butte. They mainly consist of a porous aggregate of spherules <50 μm in diameter. The spherules are dominated by magnetite dendrites in an olivine-rich silicate matrix (Fig. S3). The full characterization of these particles remains to be completed. Similar aggregates $\approx$20 μm in size (and/or disaggregated spherules) have been described previously in only 1 of the 2 extraterrestrial dust-rich layers in the Dome Fujii and EPICA Dome C (77°19′ S − 39°42′ E and 75°06′ S −123°21′ E, respectively; see Fig. 1*A Inset*) east Antarctic ice sheet cores, namely the 2,833- and 2,788-m-deep layers with a model age of 481 ± 6 kya (23). The unique characteristics of the above aggregates suggest that they are from the same event recorded in the ice cores, thereby documenting a continental scale distribution of the extraterrestrial debris associated with a major meteoritic event over the whole Antarctic continent.

The interior of the sectioned particles show no-to-moderate terrestrial weathering (Fig. S4) allowing the definition of micrometeorite types and compositions in all cases. For instance, complete barred and porphyritic olivine cosmic spherules occur together with others showing some loss of olivine at their margins, similarly to Novaya Zemlya cosmic spherules (9), whereas 1 G-type spherule showed some loss of glass. Scoriaceous and porous unmelted micrometeorites may contain secondary sulfate minerals (typically jarosite) encrustations on their external surfaces or in their voids. The metal grains in the micrometeorites of ordinary chondrite composition are variably substituted by iron oxides due to terrestrial weathering. The range of weathering levels attests to the varied terrestrial residence times of the different particles. The presence of a number of glassy cosmic spherules in our set is per se evidence in support of minor terrestrial weathering of the deposit (18).

Conclusions

We describe a unique collection of micrometeorites thought to originate through direct in fall on a continental surface, with minimal deposition of terrestrial material, apart from the local bedrock detritus, which can easily be distinguished from the extraterrestrial material. Thanks to the very old exposure age of the collection surface ($\geq$1 Myr), the studied trap has collected the long-term input of extraterrestrial material over a 0.1- to 1-Myr time interval, depending on the efficiency of the capture according to meteorological conditions and rock surface morphology. Despite their old terrestrial age, micrometeorites appear to have suffered little alteration, thanks to the dry and cold Antarctic plateau conditions, and the population shows no detectable size and compositional bias with respect to the most pristine micrometeorite collections at least in the size fractions ($>$200 μm) investigated in detail in this study. Future more detailed analyses of this collection are expected to provide a better definition of the composition of the long-term average extraterrestrial flux, compared with short-term ($<$1,000 yr) collections (in glacier ice) or weathering-biased collections (in deep sea sediments). Indeed, there are no long-term data on unmelted micrometeorites, whereas short-term collections may not sample the compositional flux variability induced by chaotic movements in source bodies (comets and asteroids). The finding of chondrules, ordinary chondritic material, and unique particles likely associated with a continental scale episodic meteoritic event $\approx$480 kyr ago within the thousands of "giant" micrometeorites (0.4–2 mm) so far found provides a hint of the great potential of the Transantarctic Mountain collection for remarkable advancements in micrometeorite study. We predict that our sampling of the micro-to-macrometeorite transition will bridge the gap between these 2 types of extraterrestrial materials, providing further insight into the paradox of their claimed distinct cometary versus asteroidal provenance.

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